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The U.S. Army, Marine Corps Kinetic Energy Program investigates advanced heavy metal kinetic energy penetrator materials and advanced high strength, light weight sabot materials and designs. In support of this, a projectile material selection methodology is presented which offers a framework for a rational, scientific approach to the complicated technical and programmatic challenges involved. Issues addressed include: standardizing weapon system constraints, performing a detailed threat assessment, formulating individual projects within funding and time constraints, and evaluating the technical issues involved with interior ballistics, aerodynamics, and terminal ballistics, along with the many sub-categories of scientific interest to the materials investigators.

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METHODOLOGY FOR KINETIC ENERGY PROJECTILE MATERIAL SELECTION

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METHODOLOGY
FOR
PROJECTILE MATERIAL SELECTION

1.0 OBJECTIVE

The purpose of this methodology is to provide sufficient information in a useable format for decision makers to make reasoned decisions on kinetic energy projectile material selection.

In order to generate the required information for materials selection, the ramifications of technical design, prototype development, full-scale production, operational and programmatic issues of different materials used in kinetic energy armor penetrating ammunition must be investigated.

Furthermore, the selection of suitable, superior sabot and penetrator materials and material combinations, for which this program methodology is to provide selection criteria, must be performed as a sub-set of a projectile development effort. In other words, the utility of a material can only be judged on the basis of the success of the projectiles they are part of. To this end, for each candidate penetrator material presented, associated sabot materials must be considered, and the evaluation of these material combinations must carry through to complete projectile designs.

2.0 TERMINOLOGY

- The Penetrator -- the projectile component which provides the kinetic energy armor defeat.

- The Flight Projectile -- that which flies to and impacts the target, normally comprising the penetrator and sometimes a penetrator sheath, the stabilizing fins if fin stabilized, and an aerodynamic nose cone.

- The Sabot -- a full-caliber structural component which supports a sub-caliber flight projectile during launch and is discarded upon exiting the gun tube. This component provides a mechanism for sealing the cannon pressure and accelerating the flight projectile.

- The K.E. Projectile -- the complete sabot and flight projectile assembly.

- The Cartridge -- the assembled round of ammunition, comprising the K.E. projectile, propellant, ignition system, and cartridge case assembly.

- Internal Ballistics -- the study, design, analysis, and testing of phenomena associated with launching a projectile from a cannon by using gas pressure. This includes the study of propellant design, cannon structural design, projectile structural design, and their associated materials and performance interactions and tradeoffs.

- External Ballistics -- the study, design, analysis, and testing of flight projectiles and their associated aerodynamic and trajectory performance, including drag, stability, and dispersion.

- Transitional Ballistics -- a sub-set of external ballistics covering the region where cannon muzzle effects influence the initial conditions of the flight projectile, including sabot separation, reverse flow, and gun tube jump.

- Terminal Ballistics -- the study, design, analysis, and testing of target defeat phenomena and the associated target kill, including kinetic energy penetration mechanisms, and behind armor effects.

3.0 THE OVERALL PROGRAM EFFORT

The emphasis of this program is placed on the application of materials in both the kinetic energy penetrator and the accompanying sabot, since the interaction of these components is inseparable within an overall projectile system.

Figures 1 and 2 present the overall program effort and where material options enter into the analysis.

Figure 1 presents the K.E. projectile design challenge with respect to the threat requirements and the need to design within certain weapon system constraints and ever present program funding and time constraints. A best feasible solution is arrived at, as opposed to an optimal solution, because of the highly empirical and artistic nature of projectile design. All design, analysis and testing tools and techniques are not exact sciences, and there exists considerable debate among the community over the best

THE OVERALL PROGRAM EFFORT

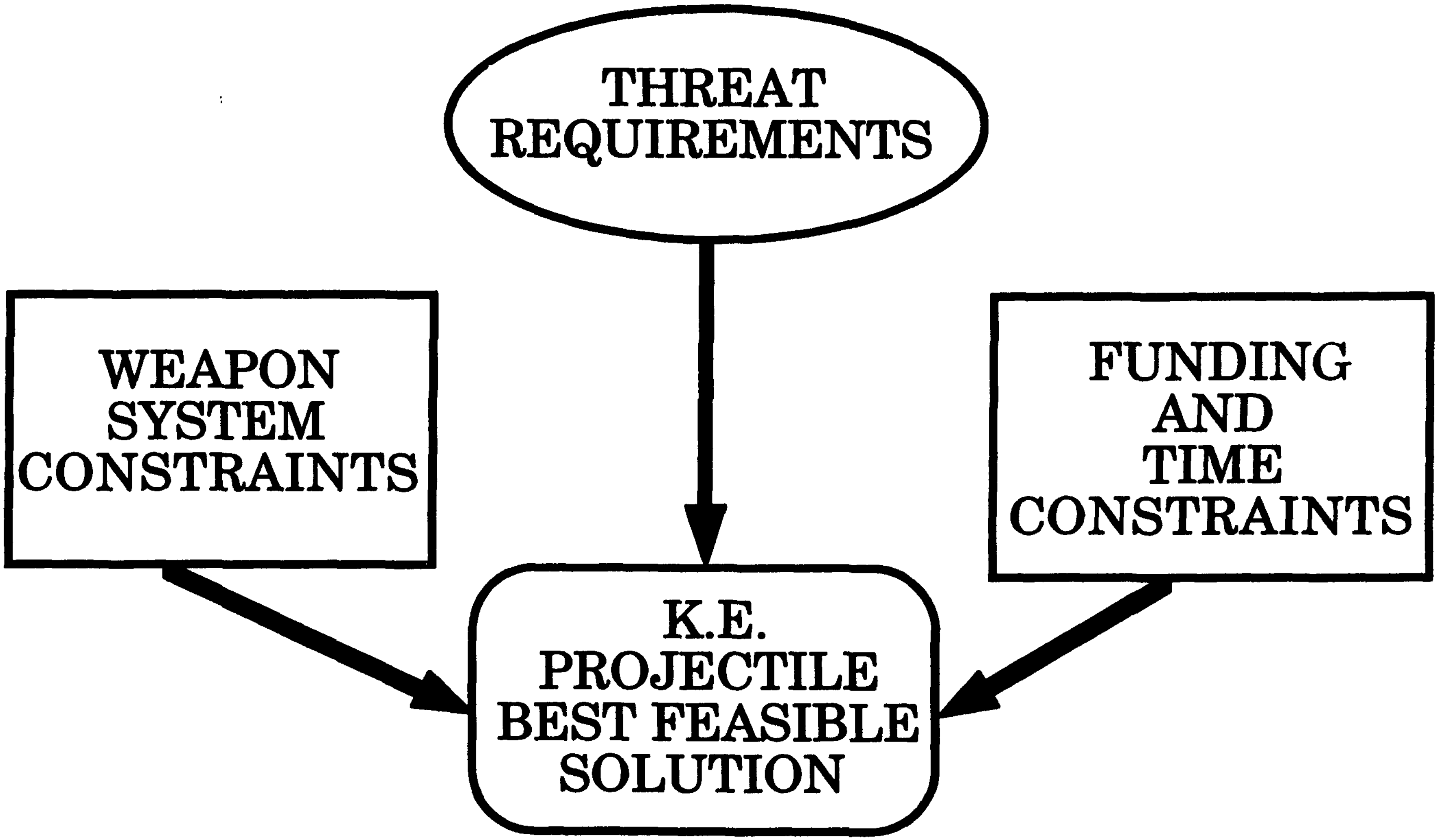

figure 1

K.E. PROJECTILE BEST FEASIBLE SOLUTION RESULTS FROM AN ITERATIVE SYSTEMS ANALYSIS PROCESS

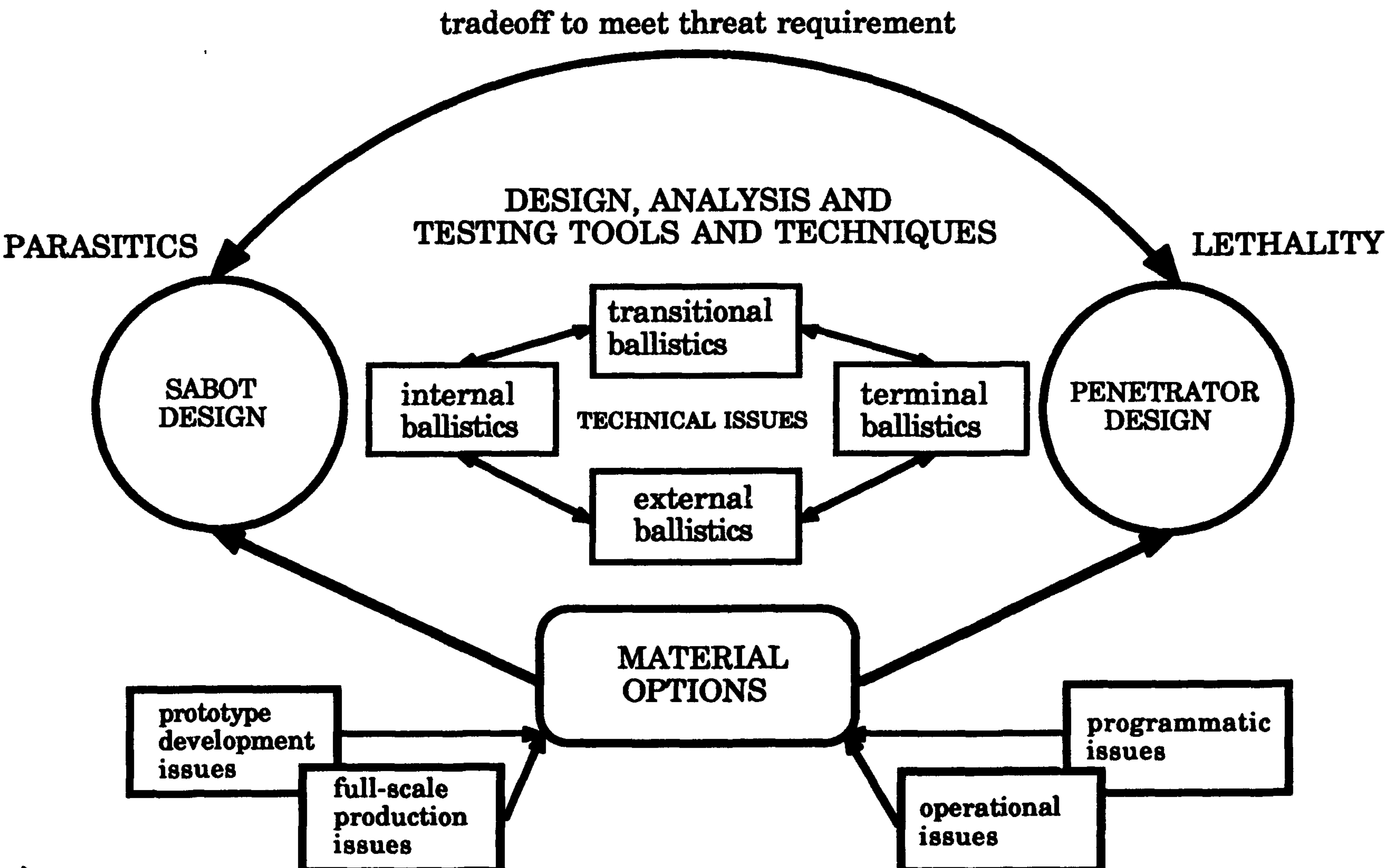

figure 2

approaches to use. Therefore, at this point in the evolution of ballistics, this investigation attempts to present the best solutions achievable within the overall program level of effort.

Given this big picture of requirements and constraints, figure 2 shows that the development of the projectile best feasible solution is the product of an iterative systems analysis process. The tools of this process are the internal, transitional, external, and terminal ballistic methodologies which the community has been developing and perfecting for decades. Normally, this process involves design tradeoffs between the projectile parasitic sabot and the lethal penetrator, with the goal being to cost effectively develop a projectile which meets or exceeds the threat requirements and fits within the system constraints.

The inputs to this systems analysis process are the projectile and penetrator materials, of which this program is challenged to evaluate. Additional inputs, which affect material selection, are operational, programmatic, prototype development and full-scale production issues.

3.1 Program Constraints

3.1.1 Funding and Time Constraints

Funding and time constraints will force a prioritization of the detailed investigation of the program issues, whether that investigation is simply information gathering or more complex experimentation. However, enough information should be initially collected on all issues and sub-issues to permit the decision maker to competently prioritize and to effectively allocate resources for follow-up research in areas of greater significance to the materials study.

Since various ballistic research efforts are on-going in the community, a program schedule must also be developed to indicate suspense dates for the incorporation of new information and techniques in each phase of the study. However, the program should be flexible to allow last minute inputs, but not to the point where entire blocks of research are unjustifiably delayed. On the other hand the program should remain relevant upon completion. Therefore, depending on the degree to which new information on ballistic techniques becomes proven technology during the study, results may be presented as both state-of-the-art, and as qualified projections of future capabilities of a particular system.

3.1.2 Weapon System Constraint Standardization

The weapon system or family of weapon systems in which the projectile designs are to be used must be standardized to ensure that any two material designs are compared against equivalent constraints. For example, it becomes difficult to compare the performance of sabot material A used with penetrator material B against sabot material A used with penetrator material C, if one is fired from a 105 mm gun and the other from a 120 mm gun. The muzzle velocity, projectile acceleration, projectile structural and overall performance depend on the gun system parameters.

The parameters of each weapon system defines certain projectile design constraints. which must be adhered to if the projectile design is to be considered a feasible, usable, realistic representation of a material's performance. These constraints are not necessarily unwaverable in the effort to develop a projectile which defeats the defined threat. However, a change in system constraints warrants an investigation into the practical, cost effective nature of the newly defined launch system, which may have a different impact on logistics, mobility, and cost, to name a few issues. Under this program effort, therefore, it may be worthwhile to constrain the problem to existing or approved future weapon system designs.

The following weapon system parameters become important constraints to the projectile design problem:

- Tube diameter
- Tube length
- Smooth bore or rifled tube
- Chamber volume and dimensions
- Cartridge case size, shape, and material composition
- Ignition system performance, requirements, and limitations
- Operating pressures (design safety factors, temperature effects)
- Operating environment temperatures (effects on materials)
- Recoil limits
- Muzzle blast restrictions
- Suitable propellant types (impacts on barrel wear, safety, etc)
- Cartridge size envelope (chamber dimensions, autoloader)
- Cartridge weight restrictions (impacts on logistics, autoloader)

3.2 Threat Definition

It must be assumed that this endeavor is undertaken to satisfy a requirement to defeat an armor threat. This threat may be defined in as

simple a set of terms as an RHA penetration with a certain amount of residual to ensure a target kill at a given maximum range, or in as complicated a set of terms as the complete line of BRL range targets at multiple engagement ranges. The former is preferred for its simplicity; the latter for its completeness.

Threat definition becomes an important preliminary program requirement for several reasons. Firstly, a systems study must be do-able in a reasonable amount of time to remain relevant to the current state of technology, and exhaustive target testing is time consuming. This and funding constraints require a simplified threat. Oversimplification, however, may underestimate the real threat and ultimately place in jeopardy the usefulness of any conclusions and recommendations which may result from the study.

Secondly, a baseline set of targets or threats must be established against which all empirical data and analysis can be reliably compared. Complications arise when comparing data on projectiles fired at different targets. There is no reliable way to convert the result to a common basis of performance when considering different targets. Therefore, as with the gun system, the target set must be standardized.

The threat definition should also contain the required projectile dispersion and system accuracy at required ranges, for the reasons that projectile design variations can present challenges to achieving this. Additionally, achieving a target hit and penetrating the armor array may not assure the desired target kill, depending on the nature of the threat vehicle. The threat requirement should also provide criteria for evaluating target kill based on armor defeat. Again, this can be defined in simple terms as a residual penetration or as an exit hole diameter with a certain amount of spall mass and velocity, or in detail as an entire vehicle vulnerability analysis.

Establishing a threat defeat requirement as a material selection criteria means that it is entirely possible that all material combinations could have feasible solutions, should the threat not be very challenging or if the weapon system is very powerful. This is not necessarily bad; however, some measure of material combination growth potential also has to be tested. Since the threat is expected to evolve, and this study should provide useful information for countering an evolving threat, a target set should be developed which represents various projections of threat protection levels. A target set comprised of various array types is also

required for testing penetrator design robustness, a necessary quality for dealing with fast changing and evolving threats.

Whatever the degree of threat definition, the time must be taken at the outset of the program to ensure that a reasonable consensus can be reached on all aspects of it.

4.0 Issues To Be Investigated

Based on the system constraints and the threat requirements, the following program issues shall be addressed in the assessment of applicable kinetic energy armor penetrating projectiles made from various penetrator and sabot materials.

4.1 Technical Issues Involving Design, Analysis and Testing Tools and Techniques

4.1.1 Terminal Ballistics

•Penetrator concepts, to include materials and geometry.

•Effects of impact velocity, obliquity and yaw on armor penetration.

•Evaluation of behind armor results which enhance lethality.

•Effects of complex targets (impact of spaced plates on penetrator stability, non-metals, etc.)

•Reactive armor effects.

•Robustness of penetrator designs

•Scaled target reliability

4.1.2 External and Transitional Ballistics

•Evaluation of flight projectile concepts, as related to candidate materials.

•Assessment of flight dynamics effects, such as aero-elasticity and drag, on the flight stability, terminal ballistics and accuracy of the projectile at various ranges.

•Assessment of the effects of in-bore balloting, muzzle phenomena, and sabot discard on the external ballistics of the flight projectile.

4.1.3 Internal Ballistics

•Impact of sabot design on the structural integrity of the flight projectile, to include sabot materials, geometry and the sabot-penetrator interface, and the effects of in-bore balloting.

•Ability to achieve the required projectile muzzle velocity for target defeat.

•Impact of projectile volume, length, mass, and performance on the gun system requirements.

•Barrel wear

•Sabot aging effects (moisture pickup, brittleness, etc.)

•Pressure history, (Pmax, etc.), which specifies the accelerations experienced by the projectile.

•Environmental conditions, i.e., operations from -45 to 145 F, coefficients of thermal expansion, sabot-projectile interface compatibility, embrittlement, etc.

4.2 Prototype Development Issues

•Full-scale and sub-scale testing issues (how small can sub-scale be and still be acceptable, scale-up issues for target and penetrator)

•Performance analysis and simulation

•Tooling and hardware manufacturing

•Facilities (manufacturing, machining, assembly, and storage)

•Developmental Cost

•Producibility, uniformity, inspectability, quality assurance

•Raw material characterization and acceptance limits on specifications

•Projectile material characterization and acceptance limits on specifications.

•Material performance as a function of environmental conditions and aging.

•Requirements for shipping, e.g., drop testing, etc.

4.3 Full-Scale Production Issues

•Establishing production base (facilitization)

•Specialized machinery, tooling, and processes

•Raw material stockpile and storage, logistics of resources

•Production quantity versus costs

•Producibility, uniformity, inspectability, quality assurance

4.4 Operational Issues

Penetrator and sabot material options shall be evaluated for impact in the following areas.

•How operational issues may impact the design of the warhead and delivery system.

•Acceptance by the services (safety, human factors, the development of inexpensive, high fidelity training surrogates).

•The environment (storage, transportation and handling, debris from testing, manufacturing refuse).

•Politics (internal to the services, local, state, federal, and international)

4.5 Programmatic Issues

Penetrator and sabot material options shall be evaluated for impact in the following areas.

•Availability of materials (peacetime, wartime, and associated costs).

•Cost (with respect to operational effectiveness, life cycle, and cost stability)

•Testing (environmental impact, safety, costs, politics)

5.0 METHODOLOGY IMPLEMENTATION

This methodology breaks the materials investigation into two broad phases. Phase I is the collection of existing information, in order to establish a base line and a starting point for commiting resources to the generation of new information. Phase II is the technical analysis phase, in which further design, analysis and testing of projectile concepts is performed, in order to create new information found to be lacking in the Phase I survey.

6.0 PHASE I -- PRELIMINARY ASSESSMENT OF TECHNICAL ISSUES BASED ON EXISTING INFORMATION

Phase I is primarily information collection, looking at the state-of-the-art in kinetic energy projectile design and the historical and current concerns and possible solutions as they relate to all the program issues. This investigation should include a presentation of accepted design, analysis and testing methodologies and any debate within the community over these techniques, as well as debate and problems associated with prototype development, full-scale production, programmatic and operational issues.

The objective of this preliminary assessment is to establish the baseline from which a determination will be made on what new information needs to be generated in the field of ballistics, relevant to material selection and projectile design, and what methodologies are best suited to doing this. Prior to beginning this Phase, however, the threat requirements and the relevant weapon system and program constraints which bound the design problem must have been established.

Information gathering should be conducted at three levels: 1) in-house search; 2) official request for information through channels from applicable institutions and agencies; 3) authorized solicitation of information directly from industry and government contacts.

The in-house search provides an informal, flexible starting point for information gathering, which will be important in finding an appropriate method of organization. Information lacking in the in-house search should

become apparent to informed investigators. These gaps can then be filled by a search of published documents from the national labs, arsenals, and agencies dealing with the relevant issues. The researchers will have to acquire bibliographies and obtain authorization to request pertinent information from these institutions.

Much of the most recent and significant research, however, may be considered special need-to-know and tucked away where others normally would not have access or even knowledge of its existence. Given appropriate official authorization, it would be fruitful to directly approach industry and government contacts, who are currently involved in the design and manufacturing of state-of-the-art kinetic energy materials and projectiles. The objectives in these one-to-one interactions are to obtain the special need-to-know information, as well as solicit these individuals' candid views, opinions, and assessments of those technical issues within their areas of expertise.

A further discussion of the Phase I tasks follows:

6.1 Selection of Candidate Penetrator and Sabot Materials

Select candidate materials, composites, and combinations of materials suitable to kinetic energy projectile penetrator and sabot design. These may be proven, existing materials or proposed developmental materials. Candidate material types may include, but are not limited to, pure metals, alloys, particulate and fibrous metal matrix composites, continuous fiber plastic composites, and combinations of the above. These materials must be categorized based on known or postulated physical and mechanical properties of interest in structural analysis and terminal ballistic analysis.

6.2 Investigation of Technical Issues

6.2.1 Terminal Ballistic Assessment of K.E. Projectiles

Based on the materials selected in paragraph 6.1, the performance of known and postulated projectile concepts will be evaluated against the prescribed threat. Whenever possible, categorization of performance will be reduced to the basic geometric and material parameters in order to allow generalization of the data. This task is an assessment of the existing body of empirical and analytical data. No attempt is made at this point to generate new performance data through testing or modeling, beyond the use of semi-empirical formulas, which may be valid for the prescribed threat.

6.2.2 Internal Ballistic Assessment of K.E. Projectiles

The body of knowledge on the design of applicable existing, fielded, experimental, and postulated kinetic energy projectiles will be assembled and categorized, based on material type, mass and geometry of sabot and penetrator components, and the internal ballistic performance of the gun and projectile. These projectile types may include traditional saddle-back and double-ramp sabot designs, and more exotic long wheel- based winged sabot designs, to name a few.

Of significant importance in this assessment are the required design safety factors and material stress levels, the design muzzle velocity, mass, and geometry of the penetrator and sabot, other parasitic mass in the projectile, placement and type of propellant, and the gun-projectile interfacing characteristics. These projectiles serve as baseline designs for their constituent sabot and penetrator materials, with comments included on the validity of the postulated designs. Note that the terminal ballistic performance of these projectiles should be identified in paragraph 6.2.1, above.

6.2.3 Transitional and External Ballistic Assessment of K.E. Projectiles

Those projectiles identified in paragraph 6.2.1 will be categorized based on external ballistic and muzzle phenomena criteria, in order to assess the impact of aero-elasticity, sabot separation, muzzle phenomena, and in-bore balloting on the accuracy and terminal ballistics of the flight projectile. These parameters influencing the resulting performance of the projectile provide a baseline and perhaps a boundary in the design of more exotic projectiles. For this reason, what is known of existing flight dynamics issues as they apply to these projectile designs must be identified.

6.3 Assessment of Operational Issues

This task involves investigating the public record and linking up with agency, department, industry, and service liaison officials responsible for establishing the applicable policies and procedures.

6.4 Assessment of Programmatic, Prototype Development, and Full-Scale Production Issues

There exist agencies and departments within the government and services which maintain information on these issues. This task will involve researching the data base on material availability, supply, and costs, and

evaluating their impact on life cycle costs, cost effectiveness, and cost stability. Manufacturing data could be obtained directly from producers, and incorporated into the costing formulas.

6.5 Report on Materials, Technical, Operational, Programmatic, Prototype Development, and Full-Scale Production Issues

This preliminary survey report should be a comprehensive assessment of the state-of-the-art in kinetic energy projectile materials and designs. There will be gaps in the report, since all existing and postulated materials and combinations have probably not been previously considered or evaluated, either empirically, analytically, or by simulation. This, however, is the value of the report, for it identifies the gaps that may be worth investigating. This forms the basis for Phase II of the investigation.

7.0 PHASE II -- TECHNICAL ANALYSIS

The level of effort in this phase is based on the need to perform additional analysis and generate new information on penetrator and sabot material performance in kinetic energy projectiles.

This analysis and design should be performed by experts in the fields of materials, structural design, and internal, transitional, external, and terminal ballistics of kinetic energy penetrators and projectiles. Necessary analytical tools include semi-empirical armor performance models, lumped parameter internal ballistic software, and three and six degree-of-freedom trajectory codes. There are also valid semi-empirical codes for determining the necessary projectile aerodynamic performance coefficients. An approved tool for structural analysis is the finite element method. This technique is valuable for evaluating the structural integrity of projectiles during launching, and for evaluating dynamic structural performance issues such as in-bore balloting and aero-elasticity.

7.1 Down Selection of Materials and Combinations

A down selection of material options should result from the evaluation of the issues presented in the Phase I report, surrounding the use of certain types of materials and combinations in kinetic energy ammunition.

7.2 Best Feasible Design Development

Beginning with the projectile characteristics need to defeat the threat, and working backwards within the system constraints, the known

principles of projectile design identified in Phase I are applied to develop new projectile concepts and material combinations, or to improve upon the existing designs. This task is an iterative process of internal, external, and terminal ballistic analysis and design to achieve the best feasible projectile system to defeat the threat. The materials selected for this task should come from the materials down selection, paragraph 6.1.

7.3 Terminal Ballistic Analysis

For those best feasible kinetic energy projectile designs developec paragraph 7.2, terminal ballistic performance must be assessed, with respect to the prescribed threat. This may be partially accomplished through the use of the various semi-empirical equations developed in the past. These formulas are not perfect, however, and may have in some cases significant margins of error. Subtle improvements in penetrator designs may not show significant benefits if these changes are out of the range of the formula's base of test data. Hydrocodes offer other insights into armor penetration phenomena. Nevertheless, their modeling equations have similar restrictions which qualify their results. The final answer on any ballistic performance, therefore, is based on actual testing of the design. Given funding and time constraints, however, there will have to be a judicious balance between the degree of emphasis on analytical determination of ballistic performance and sub and full-scale testing of actual designs

7.4 Internal Ballistic Analysis

The internal ballistic analysis of the designs will be used to evaluate the structural performance as well as the ballistic performance of the projectile. The objective is to launch a projectile with the highest possible muzzle velocity, within the constraints of projectile and cannon material strengths and safety factors. Lumped parameter analytical computer codes are very accurate at predicting muzzle velocities and cannon pressures, among other things. The pressure history output also allows the structural analysis of the projectile, using finite element techniques. This is the currently accepted analytical method of designing projectiles to meet government performance specifications.

New, unproven materials and combinations, however, will require component and full-up round testing in order to verify structural integrity, material failure criteria and material strength specifications. Manufacturing inconsistencies will also affect actual test performance, and this data is necessary for establishing adequate design safety factors,

which may reduce actual projectile performance from theoretical performance.

7.5 Transitional and External Ballistic Analysis

Flight dynamics and aerodynamics issues such as aero-elasticity, drag, yaw, sabot separation, etc. can be evaluated with the aid of specialized analytical codes and semi-empirical formulas based on previous observations. Six degree of freedom trajectory codes are an acceptable method of estimating projectile dispersion based on muzzle and in-flight disturbances. Semi-empirical codes are also used to estimate projectile drag and other aerodynamic coefficients.

7.6 Projectile Component and Prototype Testing

As a final check on analysis and simulation, several concepts should be manufactured and range tested against the prescribed threat. Testing of these designs will provide hard data on the internal, external, and terminal ballistic performance of best feasible designs and materials.

7.7 Report on The Performance of Best Feasible Designs

Those best feasible designs developed in Phase II are categorized for inclusion in the information base of existing systems identified in Phase I. The objective of this report is to fill in the gaps for those material and design concepts for which there existed no reliable performance information, and this report forms the basis for a technical assessment of candidate materials.

7.8 Update The Assessment of the Operational, Programmatic, Prototype Development, and Full-Scale Production Issues

Given new information obtained through analysis, and prototype manufacturing and testing, the body of knowledge developed in Phase I may be expanded.

8.0 MATERIAL COMBINATION SELECTION MATRIX

The information collected must be compiled into a format that facilitates both comparison of candidate systems and down selection of material options. A decision matrix is one method of compiling data that may be used. The basic concept is to refine evaluation criteria to a level where they can be compared empirically. This empirical data will then be

combined into technical evaluation matrices, as shown in the following figures, to provide a tool for objective evaluation of competing systems.

The decision matrices presented hereafter are only examples of possible evaluation criteria, and the given rankings are purely hypothetical.

EVALUATION MATRIX
TECHNICAL ISSUES

CRITERIA \ CANDIDATE SYSTEMS	A	B
TERMINAL BALLISTICS	1	2
EXTERNAL AND TRANSITIONAL BALLISTICS	1.5	1.5
INTERNAL BALLISTICS	1	2
PROTOTYPE DEVELOPMENT	2	1
TOTAL	5.5	6.5

In this matrix of technical issues, the candidates are rank ordered. A low number represents the better candidate, based on technical performance in each criteria. If there is a tie, as in external and terminal ballistics, the rank is split evenly. The total ranking represents the better candidate, based on technical issues. Similar evaluation matrices are prepared for the other issues.

At each succeeding level in the decision process, these evaluation matrices will be combined into a selection matrix, appropriate to that point in the decision making process. The following figure illustrates this concept.

SELECTION MATRIX

CRITERIA \ CANDIDATE SYSTEMS	A	B
TECHNICAL ISSUES	1	2
OPERATIONAL ISSUES	1	2
PROGRAMMATICS	1.5	1.5
PRODUCTION	2	1
TOTAL	5.5	6.5

The numbers entered in the selection matrix are again rank ordered based on the evaluation of their comparative performance. A low number represents the better candidate for each criteria. In the above example, candidate A received a better overall ranking in technical suitability. This is carried over from the previous evaluation matrix. Therefore, its rank on this selection matrix becomes 1 and B's ranking becomes 2. Similarly, if there is a tie in criteria, the ranking is evenly split among candidates, as illustrated in the programmatics criteria.

While the ranking assigned to competing systems in these matrices are initially objective, the decision maker can interject a subjective weighting of selection criteria based on his experience and perspective. The following matrix represents this next step in candidate selection.

WEIGHTED SELECTION MATRIX

CRITERIA	CANDIDATE SYSTEMS A		B		SUBJECTIVE IMPORTANCE
TECHNICAL ISSUES	1	1	2	2	1
OPERATIONAL ISSUES	1	1	2	2	1
PROGRAMMATICS	1.5	1.5	1.5	1.5	1
PRODUCTION	2	6	1	3	3
TOTAL		9.5		8.5	

Since a lower total score represents the better candidate, the subjective importance of each criteria becomes a handicapping factor. As a result, in this example a reversal in candidate ranking occurred.

This example has illustrated the importance of assembling the collection of empirical information into a material selection or decision matrix process. This facilitates the down selection of material options, as well as provide a basis for final evaluation of candidate combinations.